

Invisibly decaying Higgs boson in the Littlest Higgs model with T-parity

R. Srikanth Hundi, B. Mukhopadhyaya and A. Nyffeler¹

Harish-Chandra Research Institute, Chhatnag Road, Jhusi, Allahabad - 211019, India

Abstract. We show that there are regions in the parameter space of the Littlest Higgs model with T-parity, allowed by electroweak precision data, where the Higgs boson can decay invisibly into a pair of heavy photons A_H with a substantial branching ratio. For a symmetry breaking scale f in the range 450-600 GeV, the $\text{BR}(H \rightarrow A_H A_H)$ can be up to 95% for an intermediate mass Higgs, and from 20% down to a few percents for a Higgs boson of mass 200 GeV or above. The total decay width of the Higgs boson can thereby be enhanced by an order of magnitude compared to the Standard Model for Higgs masses around 130 GeV.

Keywords: Non-standard-model Higgs boson, Invisible Higgs decay mode, Discrete symmetries

PACS: 14.80.Cp, 12.60.Fr, 12.60.Re, 11.30.Er

INTRODUCTION

Little Higgs models [1] have been proposed as a solution to the little hierarchy problem of the Standard Model (SM), i.e. the tension between a light Higgs mass and the large scale of new physics of the order of a few TeV from electroweak precision tests. In Little Higgs models, the Higgs is a pseudo-Goldstone boson of a symmetry breaking that takes place at a scale $f \sim 1$ TeV. It gets a small mass only through radiative effects and the underlying (broken) symmetry protects the Higgs mass from getting quadratic divergences at one loop, thereby removing the little hierarchy problem. In order to ease constraints from precision tests, one can further impose a discrete symmetry, T-parity [2], which allows a rather low scale of symmetry breaking and leads to new particles in the range of a few hundred GeV and a natural dark matter candidate, the heavy partner of the photon, A_H .

A low symmetry breaking scale f raises the interesting possibility that a heavy or even intermediate mass Higgs boson could decay ‘invisibly’ into a pair of stable, heavy photons A_H which will not leave any traces in the detector, thereby leading to a missing energy signature, if T-parity is exact. Such a possibility is facilitated by the fact that the state A_H can be quite light, with $M_{A_H} \approx g' f / \sqrt{5} \approx 0.15 f$. The decay $H \rightarrow A_H A_H$ in the Littlest Higgs model with T-parity (LHT) has already been mentioned briefly in Refs. [3, 4]. Ref. [3] obtained an invisible branching ratio of about 5% for $M_H \sim 170$ GeV, if the condition is imposed that the heavy photon A_H should constitute all of the dark matter in the universe. Ref. [4] studied the production and decay of the Higgs boson in the LHT at the LHC. However, the authors of Ref. [4] only considered scales $f \gtrsim 700$ GeV where the branching ratio is smaller than 1% and therefore they did not take this decay channel into account.

¹ Talk presented by A.N. at the International Workshop on Theoretical High Energy Physics (IWTHEP 2007), Roorkee, India, 15-20 March 2007, to appear in the proceedings.

Here we will summarize our work [5] where we have shown that there are regions in the parameter space of the LHT, fully compatible with electroweak constraints, where the invisible decay $H \rightarrow A_H A_H$ can have a substantial branching ratio. Such a large invisible decay width is unlikely for the lightest neutral supersymmetric Higgs, at least in the minimal version of the theory. Therefore this invisible Higgs boson decay might help to distinguish the LHT from the MSSM at present and future colliders.

THE INVISIBLE DECAY $H \rightarrow A_H A_H$

The mass (squared) of the heavy T-odd photon A_H is given by $M_{A_H}^2 = \frac{g'^2 f^2}{5} - \frac{g'^2 v_{\text{SM}}^2}{4}$, neglecting higher powers of v_{SM}^2/f^2 . Since the heavy photon, as the lightest T-odd state, is stable, there are no off-shell decays $H \rightarrow A_H^* A_H^*$ and the channel opens up only for $m_H \geq 2M_{A_H}$. The interaction $HA_H \mu A_H^\mu$ in the LHT is described by the Feynman rule $(-i/2)g'^2 v_{\text{LHT}} g_{\mu\nu}$. The quantity v_{LHT} is obtained from $v_{\text{SM}} = 246$ GeV by inverting the relation $v_{\text{SM}} \equiv f \sqrt{1 - \cos(\sqrt{2}v_{\text{LHT}}/f)}$ [4]. The decay width is then given by

$$\Gamma(H \rightarrow A_H A_H) = \frac{g'^4 v_{\text{LHT}}^2}{2048\pi M_{A_H}^4} m_H^3 \beta_A (4 - 4a_A + 3a_A^2), \quad (1)$$

where $a_A = 1 - \beta_A^2 = 4M_{A_H}^2/m_H^2$. From Eq. (1) we see that the partial width scales like $1/M_{A_H}^4 \sim 1/f^4$.

As pointed out in Ref. [4], the couplings of the Higgs boson to the SM particles are subject to corrections in the LHT. We have used the program HDECAY [6] to calculate the partial widths of the Higgs boson in the SM in the various channels. The corresponding decay widths in the LHT have then been obtained in a simplified (and approximate) way by multiplying the SM results with the appropriate correction factors. Adding the new invisible decay mode $H \rightarrow A_H A_H$ from Eq. (1) leads to the total width of the Higgs boson in the LHT.

In Fig. 1 we have plotted for $f = 500$ GeV all branching ratios of the Higgs boson in the LHT that are larger than 10^{-3} in the mass range $115 \text{ GeV} < m_H < 600 \text{ GeV}$. One observes, that as soon as the decay $H \rightarrow A_H A_H$ is kinematically allowed, $m_H \geq 2M_{A_H} = 130 \text{ GeV}$, we get a huge invisible BR($H \rightarrow A_H A_H$) of about 75% in the Higgs mass range $135 - 150 \text{ GeV}$. The reason is that the Higgs boson couples to the heavy photons A_H with electroweak strength g' which is much larger than the Yukawa coupling to the bottom quarks. The decay width is also larger than the off-shell (three or four-body) decay $H \rightarrow W^{(*)} W^*$, unless that decay starts to grow around $m_H = 2M_W$. At $m_H = 159 \text{ GeV}$ we have $\text{BR}(H \rightarrow A_H A_H) \approx \text{BR}(H \rightarrow WW) = 47\%$. At $m_H = 200$ (600) GeV the invisible decay BR is still about 10 (5.5)%.

Below the threshold of 130 GeV, the same decay channels are open as in the SM, however, $H \rightarrow gg$ is highly suppressed in the LHT, see Ref. [4]. Since we have taken the fermion couplings from the “case A” proposed in Ref. [4], which differ not much from their SM values, there is no large enhancement of the $H \rightarrow \gamma\gamma$ mode as observed in that reference for the “case B”. As soon as the decay $H \rightarrow A_H A_H$ is possible, all other branching ratios drop down considerably.

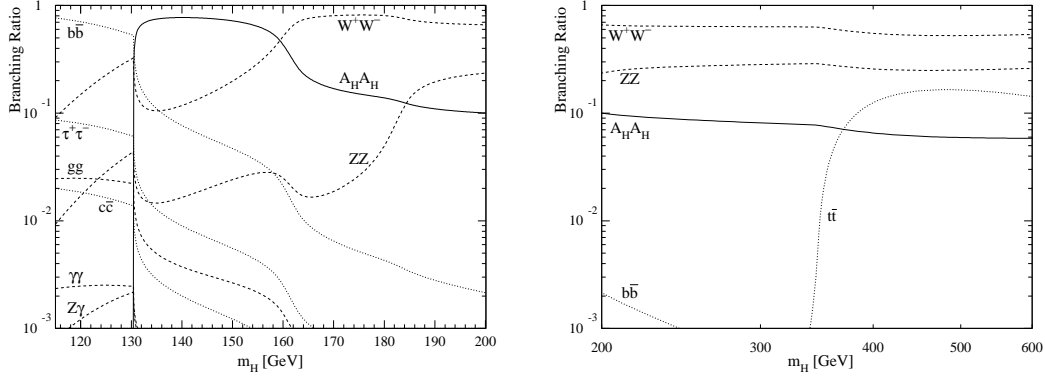


FIGURE 1. Branching ratios in the Littlest Higgs model with T-parity for Higgs masses below 200 GeV (left panel) and above 200 GeV (right panel) for a symmetry breaking scale $f = 500$ GeV.

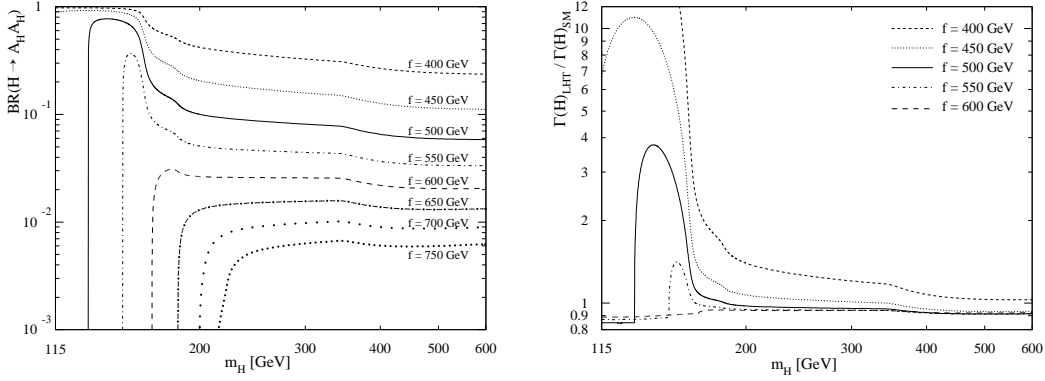


FIGURE 2. Left panel: Branching ratio for the invisible decay $H \rightarrow A_H A_H$ in the Littlest Higgs model with T-parity for several values of the symmetry breaking scale f . Right panel: Ratio of the total decay width of the Higgs boson in the LHT, $\Gamma(H)_{\text{LHT}}$, to the total decay width in the SM, $\Gamma(H)_{\text{SM}}$, for different values of f . The curve for $f = 400$ GeV peaks at a value of about 35 for $m_H \approx 126$ GeV.

Note that we have not taken into account the off shell-decays $H \rightarrow W_H^* W_H^*$ and $H \rightarrow Z_H^* Z_H^*$ for Higgs masses larger than $M_{W_H} = M_{Z_H} = 317$ GeV for $f = 500$ GeV. We expect the corresponding branching ratios to be small below the two-particle threshold.

In Fig. 2 (left panel) we show the invisible branching ratio $H \rightarrow A_H A_H$ as a function of the Higgs mass for different values of f in the range 400 – 750 GeV. For $f = 400$ (450) GeV the branching ratio can be as large as 98 (93)% for Higgs masses below about 150 GeV. Although values of $f = 400$ GeV are allowed by the precision data, the calculation cannot be completely trusted there. For such low values of f , higher derivative terms in the low-energy expansion in the LHT model, generated at the scale $\Lambda \sim 4\pi f$, should be taken into account. In this sense $f \simeq 400$ GeV marks the lower end of the parameter space where the underlying framework is reliable.

For $f = 600$ GeV, the invisible branching ratio is 2 – 3% for $m_H \gtrsim 169$ GeV, whereas

it drops below 1% for $f \geq 700$ GeV. Since the $A_H A_H$ -threshold for $f = 600$ GeV is about 167 GeV, i.e. above the WW -threshold, the on-shell decays into WW and later into ZZ overwhelm the invisible decay $H \rightarrow A_H A_H$.

Figure 2 (right panel) shows the ratio of the total decay width of the Higgs boson in the LHT, $\Gamma(H)_{\text{LHT}}$, to the total width in the SM, $\Gamma(H)_{\text{SM}}$, as a function of the Higgs mass for a subset of values of f used in Fig. 2 (left panel). In contrast to earlier studies [7, 4] which always observed a reduction of the total decay width of the Higgs boson in the Littlest Higgs model and in the LHT compared to the SM, we get a potentially huge enhancement of the decay width for values $f \leq 550$ GeV. For $f = (400, 450, 500, 550)$ GeV, the maximal enhancement factors of (34.8, 11.0, 3.77, 1.41) that can be seen in Fig. 2 (right panel) correspond to $\Gamma(H)_{\text{LHT}} = (140, 51, 30, 33)$ MeV at $m_H = (125.8, 130.2, 140.5, 153.4)$ GeV. Note, however, that the width of the Higgs boson in the SM is very small for Higgs masses below the WW -threshold. Only for $f \geq 600$ GeV we obtain a reduction of the total width for the whole range of Higgs masses $115 \text{ GeV} < m_H < 600 \text{ GeV}$. The ratio $\Gamma(H)_{\text{LHT}}/\Gamma(H)_{\text{SM}}$ varies between 0.89 and 0.95 for values of $f = 600 - 750$ GeV.

We would like to stress that there are regions in parameter space where values of $115 \text{ GeV} < m_H < 650 \text{ GeV}$ and $400 \text{ GeV} < f < 700 \text{ GeV}$ are allowed by the electroweak data at 95% confidence level, see Ref. [5] for details of the electroweak fit.

CONCLUSIONS

A substantial branching ratio into the invisible channel not only makes the Higgs boson a rather interesting object but also helps in associating it with some specific types of non-standard physics. For example, in supersymmetric theories, the lightest neutral scalar can in principle decay into two lightest neutralinos, making it invisible. However, the branching ratio of such a decay is usually not very high, and is rather restricted in the regions of the parameter space allowed by LEP data, at least in those versions of the theory not too far from the minimal model. In the LHT, however, the invisible branching ratio can not only be appreciable but also may correspond to a Higgs boson that is heavier than what is allowed in a minimal supersymmetric framework. Thus this region of the parameter space may provide a test to distinguish the LHT from supersymmetry.

REFERENCES

1. N. Arkani-Hamed, A. G. Cohen and H. Georgi, Phys. Lett. B **513**, 232 (2001); N. Arkani-Hamed *et al.*, JHEP **0208**, 020 (2002).
2. H. C. Cheng and I. Low, JHEP **0309**, 051 (2003); **0408**, 061 (2004); I. Low, JHEP **0410**, 067 (2004); J. Hubisz and P. Meade, Phys. Rev. D **71**, 035016 (2005); J. Hubisz, *et al.*, JHEP **0601**, 135 (2006).
3. M. Asano, *et al.*, Phys. Rev. D **75**, 063506 (2007).
4. C. R. Chen, K. Tobe and C. P. Yuan, Phys. Lett. B **640**, 263 (2006).
5. R. S. Hundi, B. Mukhopadhyaya and A. Nyffeler, Phys. Lett. B **649**, 280 (2007).
6. A. Djouadi, J. Kalinowski and M. Spira, Comput. Phys. Commun. **108**, 56 (1998).
7. T. Han, *et al.*, Phys. Lett. B **563**, 191 (2003) [Erratum-ibid. B **603**, 257 (2004)]; H. E. Logan, Phys. Rev. D **70**, 115003 (2004); G. A. Gonzalez-Sprinberg, R. Martinez and J. A. Rodriguez, Phys. Rev. D **71**, 035003 (2005).